A VERY-HIGH-GRADIENT TEST OF A 30 GHZ SINGLE-CELL CAVITY

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Abstract

In order to extend the available range of data on achievable accelerating gradients and pulse lengths at the CLIC (Compact Linear Collider) frequency of 30 GHz, a single-cell resonant cavity has been high-gradient tested in the CLIC Test Facility, CTFII. The cavity was excited by a 4 ns long bunched electron beam, resulting in a field pulse with a steep rise, followed by an exponential decay with a 1/*e* time of 25 ns (corresponding to a loaded *Q* of 3800). The cavity operated without breakdown at a peak accelerating gradient of 290 MV/m, with operation progressively less stable with increasing gradient. At about 400 MV/m the cavity broke down on every pulse. For this condition the cavity surface was subject to a surface electric field in excess of 750 MV/m.

1 INTRODUCTION

During nominal conditions, CLIC 30 GHz accelerating structures are to operate with an average loaded accelerating gradient of 150 MV/m, an input accelerating gradient of 170 MV/m, a peak input surface field of 410 MV/m, an input power of 240 MW, and an RF pulse length of 130 ns [1]. Progress towards demonstration of operation with these field levels has been made in CTFI (CLIC Test Facility) and CTFII [2]. The RF pulse length achievable in the test facilities has however always been limited to less than 16 ns, which is much less than the nominal CLIC RF pulse.

The experiment described in this paper was conceived as a means to achieve longer pulse lengths in the existing test facility, CTFII. In addition the experiment allows the study, in unusually simple conditions, of the processes of breakdown.

The concept behind the experiment was to power a single-cell resonant cavity directly using the high intensity CTFII beam and then to let the cavity ring freely. In this way the RF pulse length was extended from the 4 ns driving-beam time to the 25 ns field 1/*e* decay time of the cavity. The fields in the cavity rise essentially linearly during the passing of the driving train and then decay exponentially. A magnetic coupling slot in the side wall of the cavity provided a measure of the fields in the cavity and thus a way to observe that breakdowns have occurred.

2 RF DESIGN AND FABRICATION

Cavity dimensions and RF properties were determined using MAFIA 2-D. The results were confirmed, and the coupling slot dimensions were estimated, using HFSS. A precise computational determination of the coupling strength is problematic because the narrow coupling slot requires a very fine mesh density. A sketch of the cavity geometry is shown in Figure 1. The computed RF properties are summarised in Table 1. The accelerating gradient was obtained by dividing the total cavity voltage by the length of the cavity, 3.56 mm. Since the structure is not periodic this choice is somewhat arbitrary.

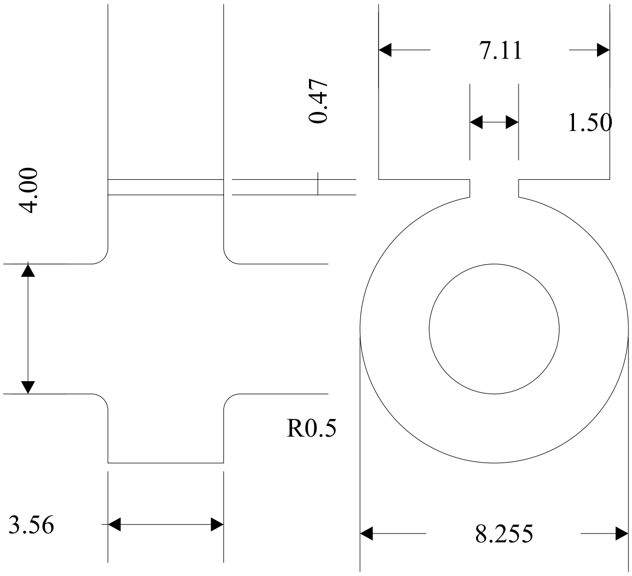

Figure 1: Side and end view of the cavity geometry. All dimensions are in mm. The beam pipe aperture is 4 mm. The WR-28 coupling waveguide emerges upwards.

Table 1: Computed and measured RF properties. k is the loss factor and E_s/E_{acc} stands for the maximum surface electric field divided by the accelerating gradient.

	calculated	measured	units
f	29.985	29.985	GHz
Q_0	5110	5040	
k	4.36×10^{12}		V^2J^{-1}
E_s/E_{acc}	1.8		

The cavity was manufactured in OFHC copper using some of the technologies developed for CLIC accelerating structures [3]. In particular, the cavity blocks were turned to a two micron tolerance and an optical quality surface finish (better than N1), and the cavity was joined using a hybrid brazing/diffusion bonding technique. A photograph of the assembled cavity is shown in Figure 2.

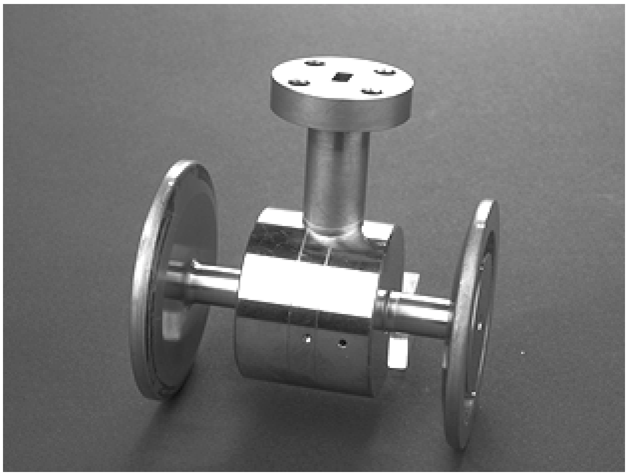

Figure 2: Photograph of the assembled cavity.

The assembled cavity was tuned to 29.985 GHz using three 1.5 mm diameter deformable tuning dimples. The measured loaded Q_l was 3800. The measured coupling factor was β=0.33 (under-coupled) giving an unloaded Q_0 of 5040.

The computed time dependence of the field amplitude of the cavity driven by a 100 nC, 4 ns long train is given in figure 3.

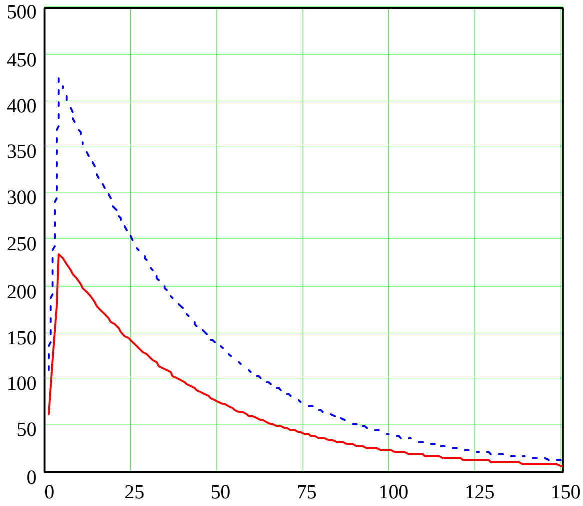

Figure 3: Accelerating gradient (solid curve) and peak surface field (dashed curve) in units of MV/m as a function of time in units of ns.

3 EXPERIMENTAL SET-UP

The cavity was installed in the high current drive beam line of CTFII about 1 m downstream of a quadrupole triplet. The triplet was used to focus the 30 mm diameter drive beam down through the 4 mm aperture of the cavity. The drive beam consisted of a train of approximately σ=2 mm long bunches spaced by 10 cm (3 GHz). A 12 bunch train, 4 ns long, was used throughout this experiment. The field level in the cavity was adjusted by varying the drive beam bunch charge. The beam energy was 45 MeV.

The high-power RF network is shown in Figure 4. The cavity output signal was sampled via a -57 dB directional coupler and then terminated by a tapered stainless steel load. The low-power 29.985 GHz RF pulse was transported out of the CTF tunnel, mixed down to 500 MHz and captured on a 5 Giga-sample per second oscilloscope. The entire RF system was calibrated so that the measured power pulse could be compared to the expected levels calculated from the driving charge and the properties of the cavity.

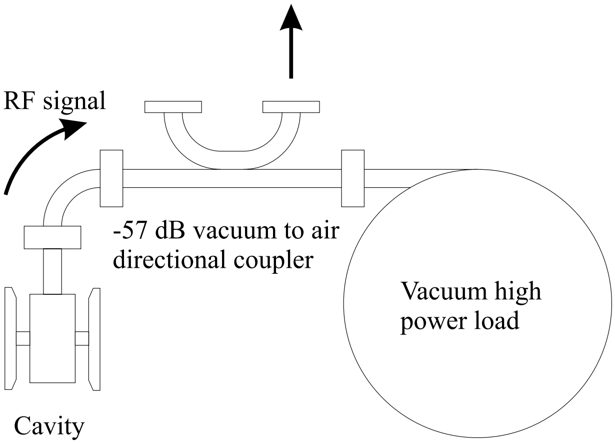

Figure 4: High-power RF network based on WR-28 waveguide.

4 EXPERIMENTAL RESULTS

The behaviour of the cavity was first investigated by gradually increasing the beam current from a low value until the first breakdowns were observed. An example of a pulse, in which no breakdown occurred, mixed down to 500 MHz, is shown in Figure 5.

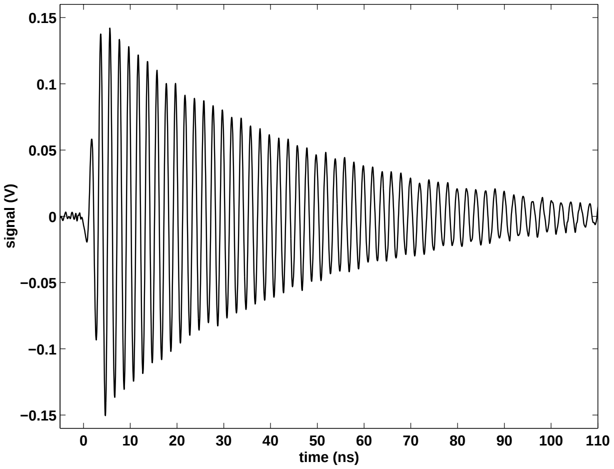

Figure 5: Cavity output pulse mixed down to 500 MHz, as captured on the oscilloscope. On this pulse there is no evidence of breakdown.

Breakdowns were signalled by an abrupt extinction of the fields inside the cavity - examples are shown in figure 6. Breakdowns began when the peak of the accelerating gradient time profile was 290 MV/m (530 MV/m surface field). As the fields were pushed to higher values, breakdowns occurred more frequently. Above 320 MV/m (575 MV/m surface field) the cavity broke down on every shot. The cavity was then pushed up to an accelerating gradient of 480 MV/m (750 MV/m surface field).

Breakdowns, for shots with peak values below 480 MV/m (750 MV/m surface field), occurred well after fields in the cavity had peaked and had even decayed to a fraction of the peak value. For pulses with peak accelerating gradients of the order of 300 MV/m (540 MV/m surface field), breakdowns occurred 30 to 100 ns after the pulse had begun. The time at which the breakdown occurred varied from shot to shot, although high field levels tended to produce earlier breakdowns. At 480 MV/m (750 MV/m surface field) the cavity broke down on every shot within a few ns after the peak value. The randomness in breakdown time is evident in figure 6, which shows the field as a function of time for a sequence of shots with constant driving charge and consequently constant peak fields. A common feature of the breakdowns was that the resonant frequency of the cavity went up during the time the field amplitude was dropping rapidly.

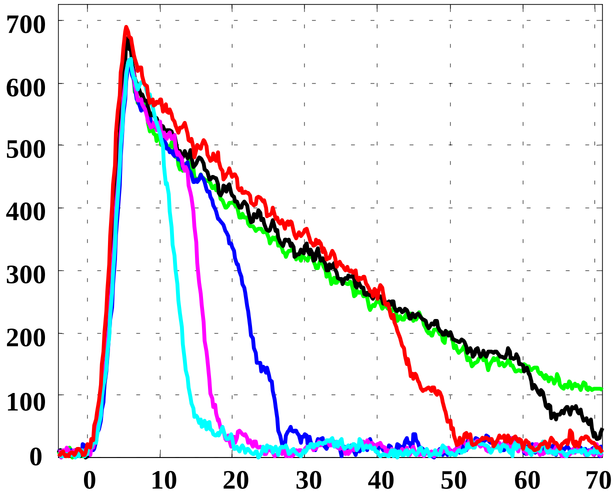

Figure 6: Field in the cavity on a succession of pulses with constant driving current. Surface field in units of MV/m is plotted against time in units of ns.

After exploring its basic breakdown behaviour, an attempt was made to condition the cavity. However, only a few hours of beam time, corresponding to about 10^4 shots, was available (the experiment was made very near the end of the 1999 CTFII run) and no conditioning of the cavity was observed .

After the experiment the cavity was inspected with an endoscope. There was no evidence of damage to the diamond machined surface of the cavity. The image quality achievable with the endoscope is limited, however, and the cavity would have to be cut open to make a definitive statement on surface damage.

5 INTERPRETATION

The most striking feature of the breakdown data is that most of the breakdowns occurred well after the maximum fields had been present in the cavity and consequently at relatively low values. This observation has led to the proposal that, as in superconducting cavities, breakdowns are caused by dust particles that are heated and then explode [4]. In the proposal, breakdown occurs after a certain value (which depends on the size of the particle) in the time integral of square of the electric field has been reached. Even if the origin is not specifically dust, breakdown caused by heating would explain why, in this experiment, breakdowns begin well after the maximum field levels have occurred. It would also predict that, for structures fed with power, the maximum achievable field should be inversely proportional to the square root of the pulse length.

An important aspect of this high gradient test is that the fields in the cavity were established with a beam rather than with an external RF source. Because the duration of the beam was 4 ns and breakdowns typically began well after 30 ns, breakdowns were not fed with additional power once they had begun. This may explain why no surface damage was observed even though the cavity was driven to extraordinarily high field levels. It may also explain why no progress was made in the attempt to condition the cavity - not enough energy was available to 'burn' off whatever initiated the breakdown.

It is important to emphasise that the very high field levels achieved in this experiment are probably not accessible to practical accelerating structures. The special features of this experiment, including the pulse shape and method of powering, probably create particularly favourable conditions for high fields. As an example, and in contrast to this experiment, prototype 30 GHz travelling wave accelerating structures have suffered surface damage after operation with accelerating gradients of only 125 MV/m.

REFERENCES

[1] J.P.Delahaye, I. Wilson, “CLIC, a Multi TeV $e^\pm$ Linear Collider”, CERN/PS 99-062 (LP), November 1999.

[2] H.H. Braun for the CTF team, “Experimental Results and Technical Research and Development at CTF II”, these proceedings.

[3] I. Wilson, W. Wuensch, C. Achard, “The fabrication of a prototype 30 GHz accelerating section for CERN linear collider studies”, CERN-SL/90-84 (RFL).

[4] G. Geschonke, W.Schnell, “Delayed RF Breakdown in a Microwave Cavity”, CLIC note 431, April 2000.